SEARCH FOR EXOTIC HADRONS IN THE 12 GEV ERA AT JLAB

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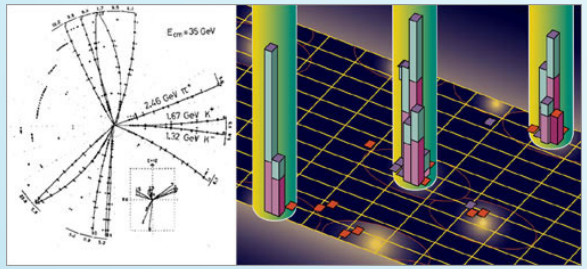
OUTLINE

- Review of QCD bound states.
- Expectations for exotic states.
- Photoproduction at 12 GeV Jlab.
- Status of current searches.
- Summary and Outlook

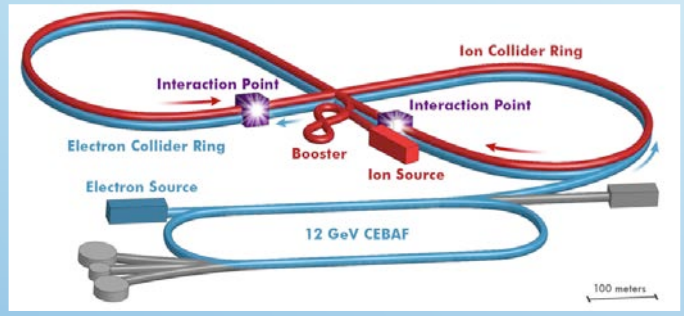
THE ROLE OF GLUE.

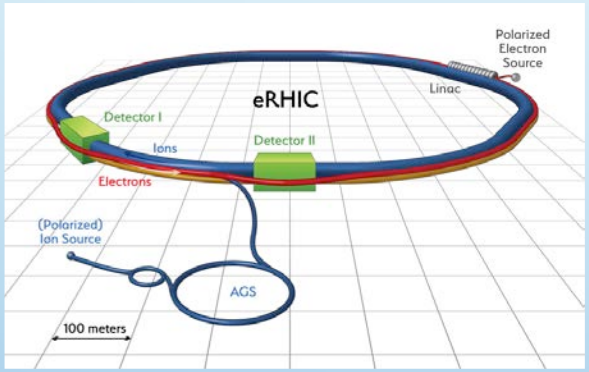


3-jet event from PETRA (1979)

Three-jet events in e^+e^- collisions demonstrated the existence of gluons.

Glue is now recognized as a significant part of hadronic matter, making major contributions to the mass and spin of the proton.

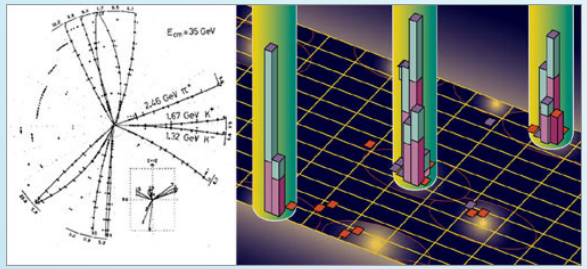




The Electron-Ion Collider, or EIC will collide electrons with nuclei and look deep inside the nucleus to reveal the role of gluons, the carriers of the strong force.

Understanding the role of glue in hadronic matter is a central theme of nuclear physics.

THE ROLE OF GLUE.



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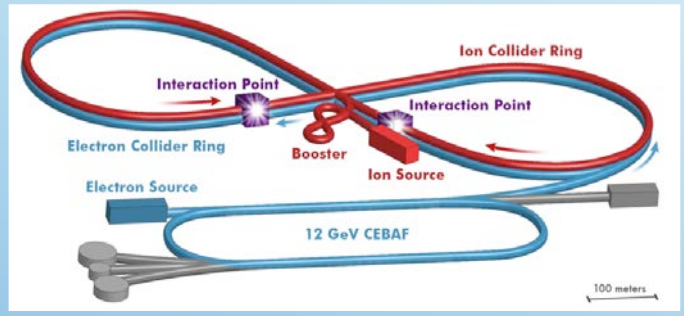

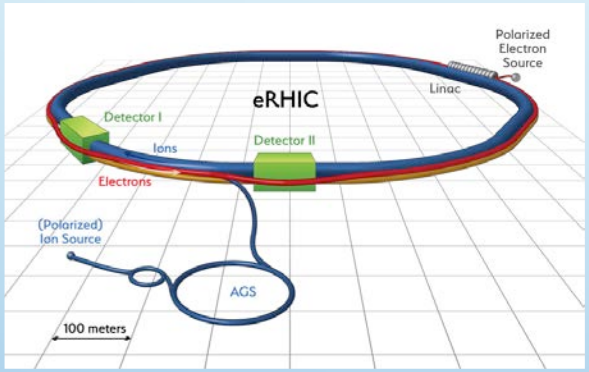

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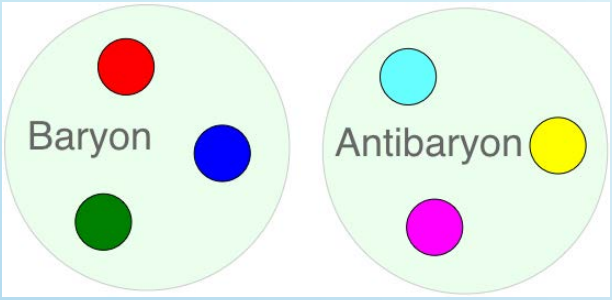
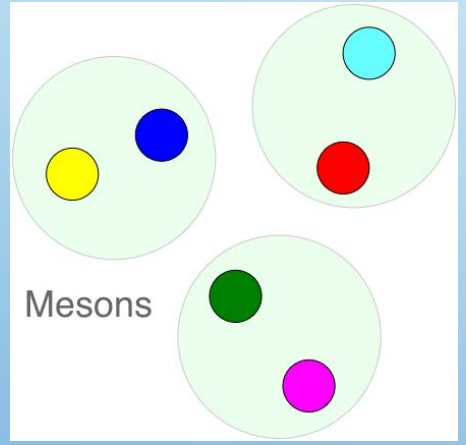
What are the gluonic degrees of freedom in bound states?

QCD Bound States

Baryons and Mesons





QCD Bound States

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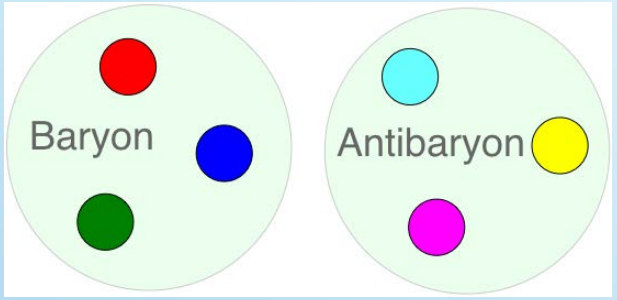

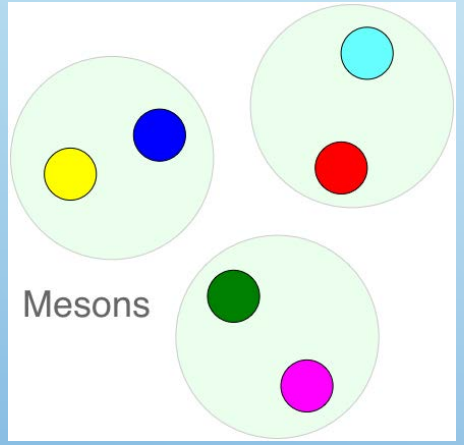

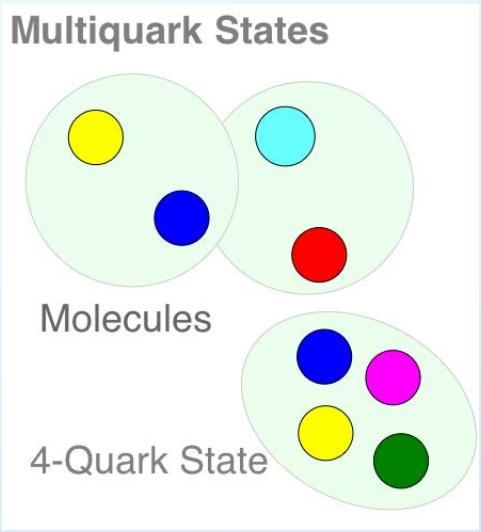

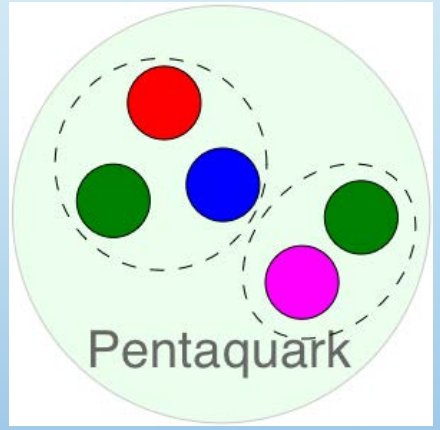

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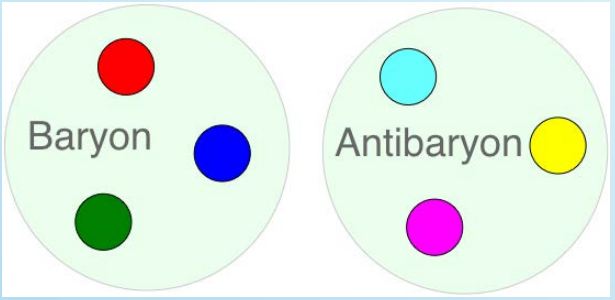

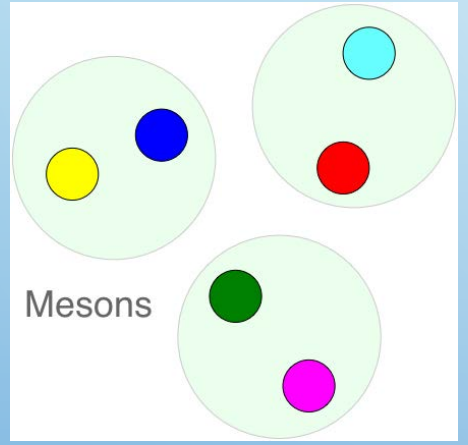

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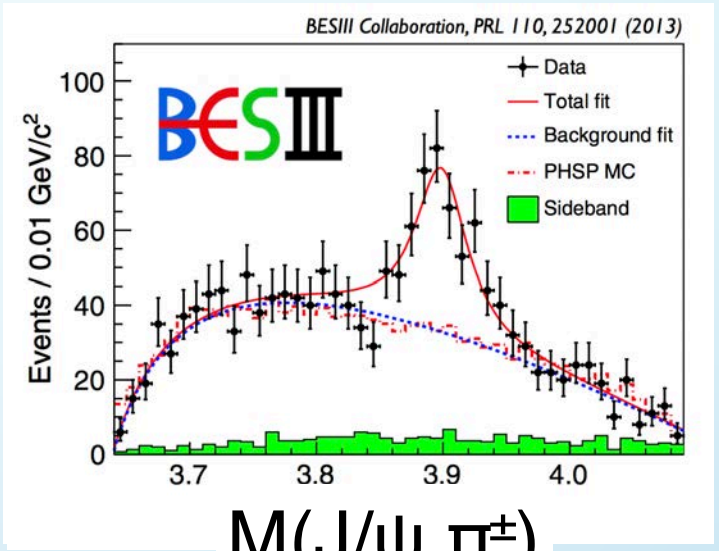
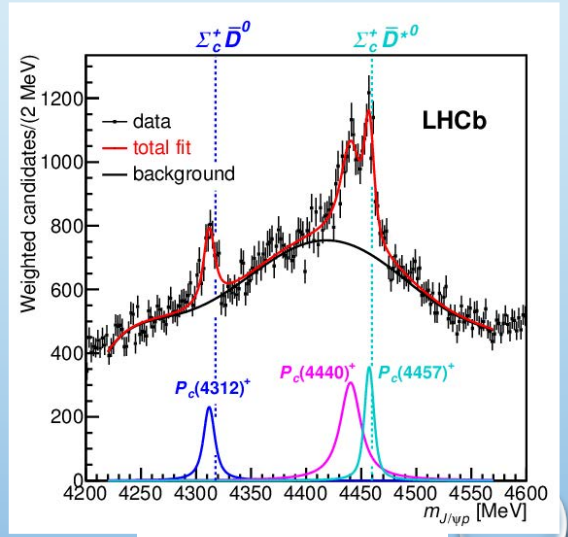


M(J/ψ π±)

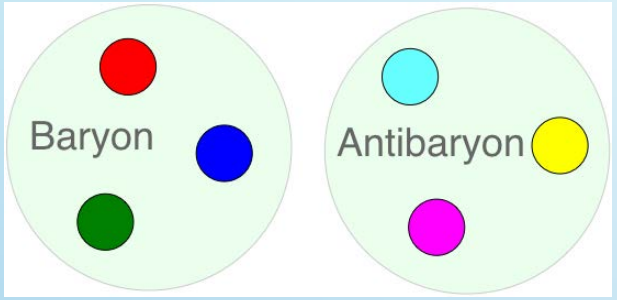
The LHCb experiment has recently reported on pentaquark candidates involving charm quarks.

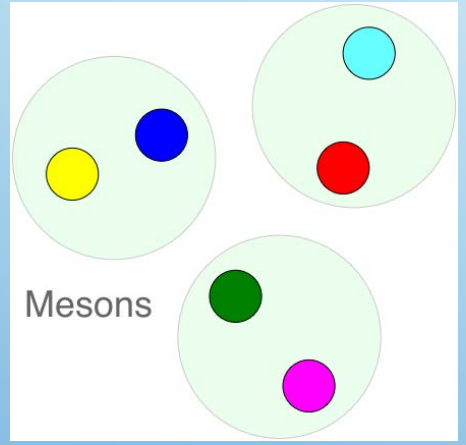


M(J/ψ p)

QCD Bound States

Baryons and Mesons





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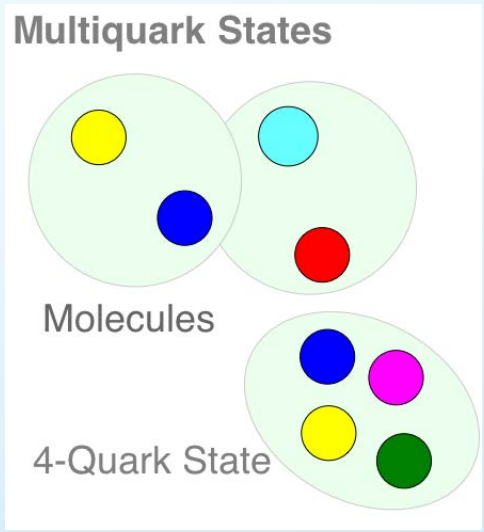
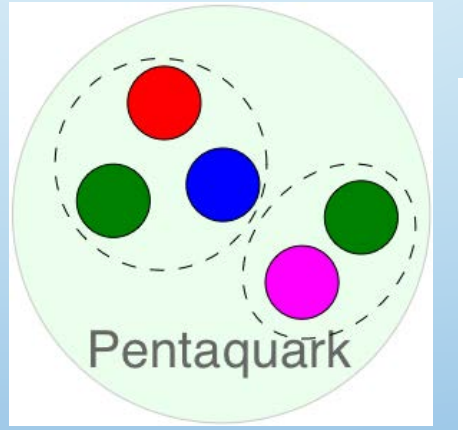
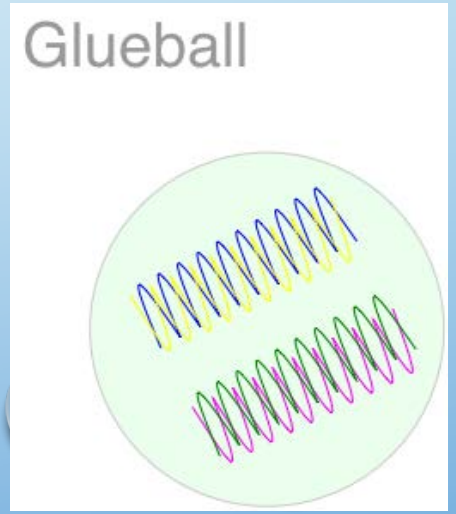
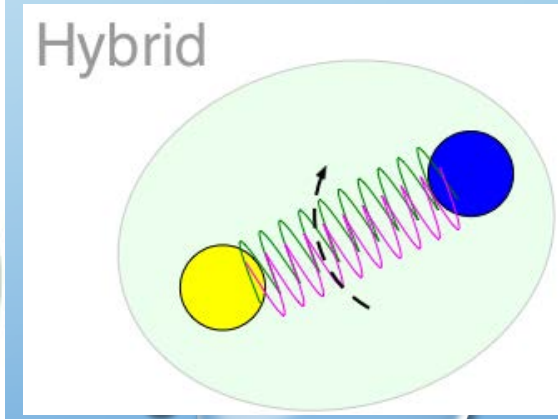




Can gluons also build color-neutral objects?

An **excited gluonic field** can contribute to the quantum numbers of a meson. Some of these quantum numbers are not possible for mesons, known as ***exotic***.





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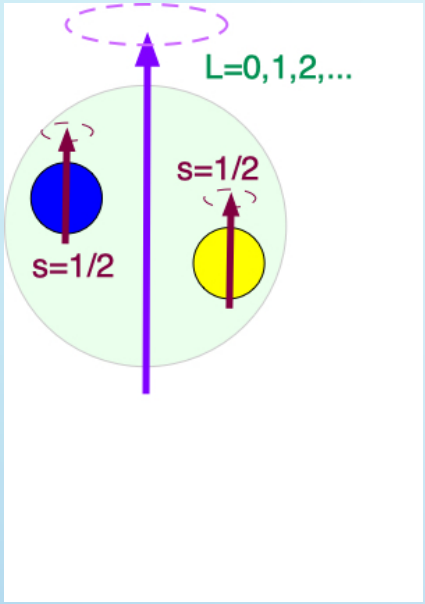
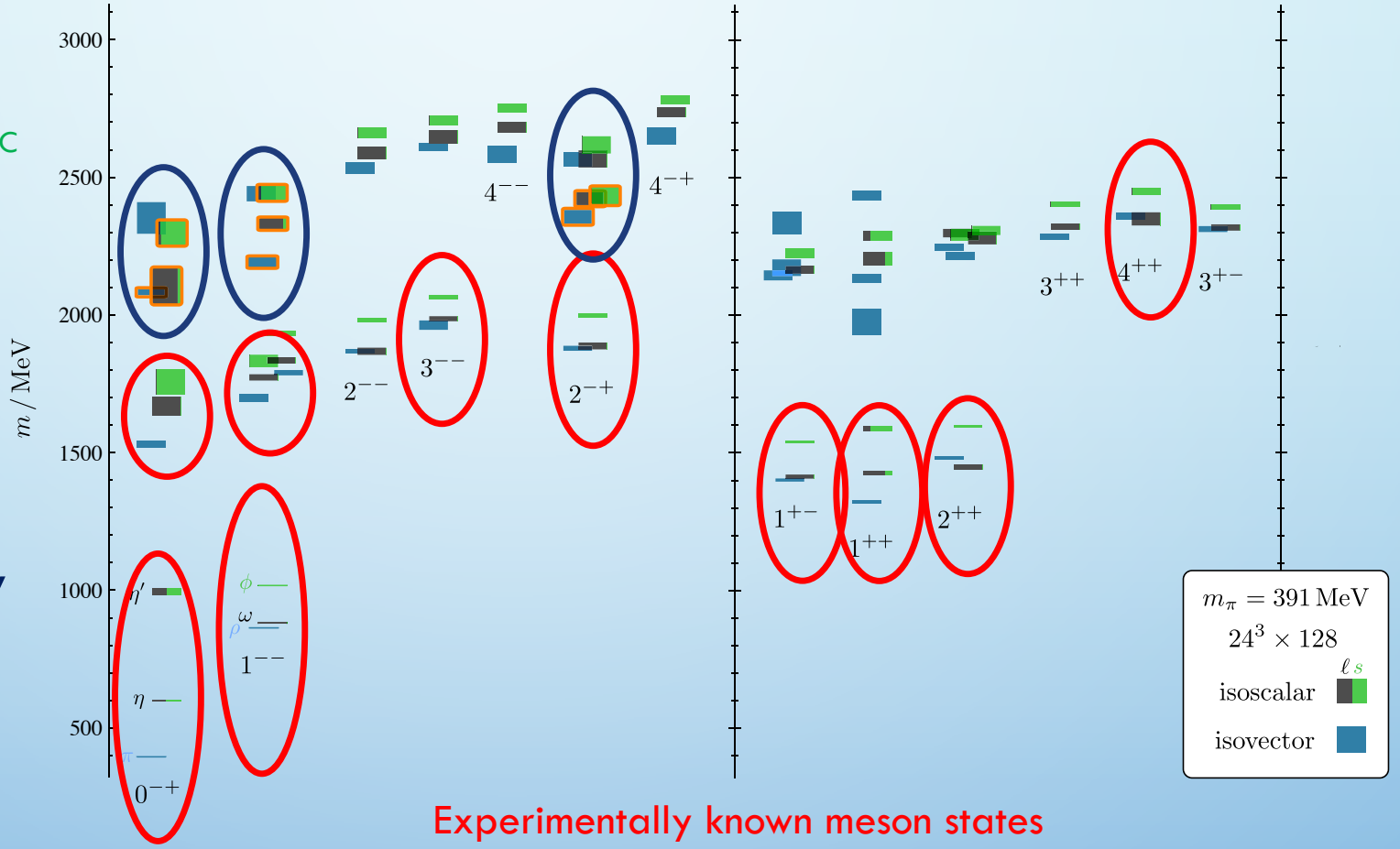


We know that mesons and baryons can be accurately described by constituent quarks being underlying degrees of freedom.

Lattice QCD calculation of meson spectrum.

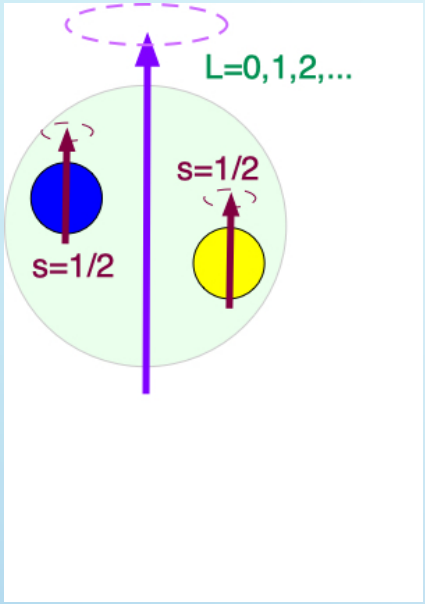


Experimentally known meson states

States whose assignment is not clear.

LQCD: Phys. Rev. D88, 094505 (2013).

THE ROLE OF GLUE.



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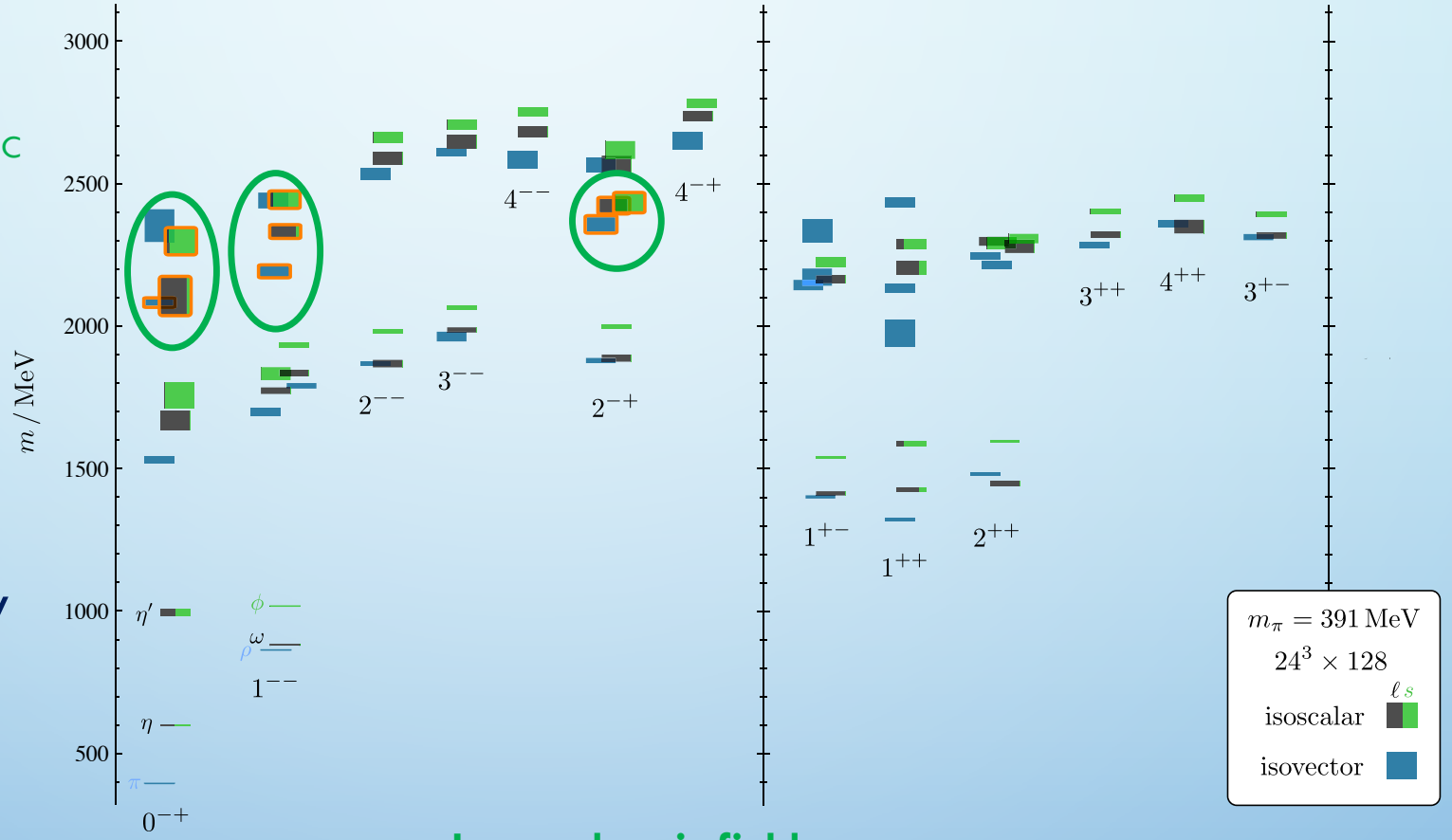
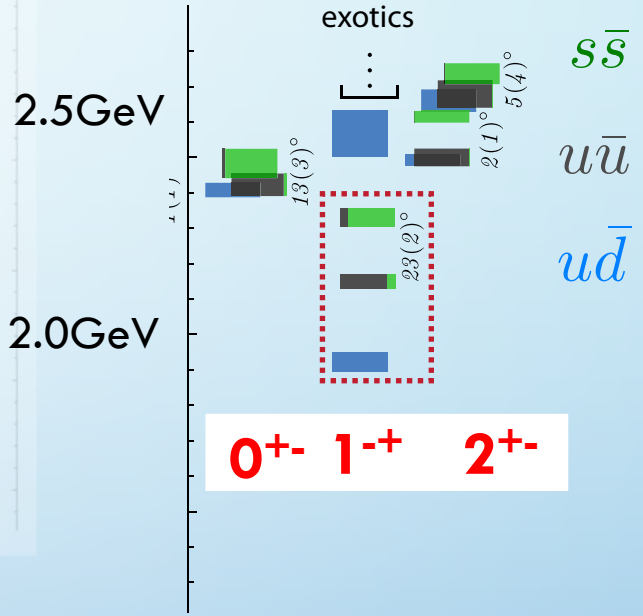


Large gluonic fields

Does glue manifest itself as an underlying degree of freedom in the hadronic spectrum?

THE ROLE OF GLUE.

Lattice QCD



LQCD: Phys. Rev. D83, 111502 (2011)

Does glue manifest itself as an underlying degree of freedom in the hadronic spectrum?

EXOTIC HYBRID MESONS

Lattice QCD suggests 5 nonets of mesons with exotic quantum numbers:

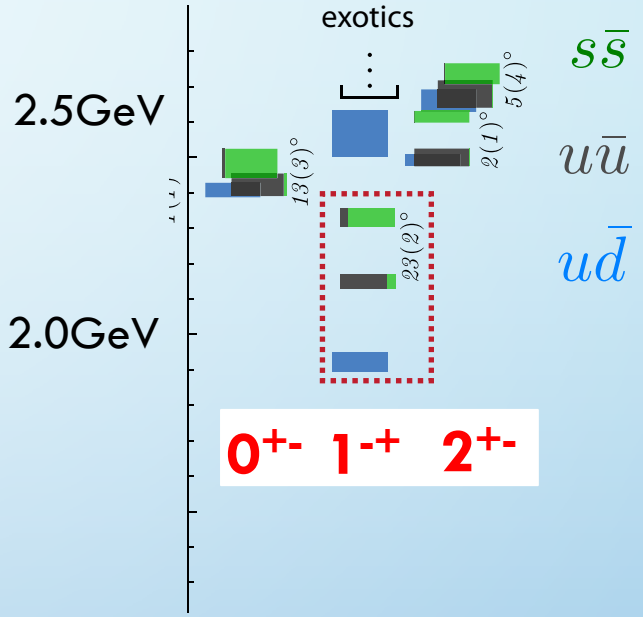
1 nonet of 0^{+-} exotic mesons

2 nonets of 1^{-+} exotic mesons

2 nonets of 2^{+-} exotic mesons

Lattice QCD results are consistent with the gluonic field behaving like a $J^{PC}=1^{+-}$ constituent with a mass ~1-1.5 GeV/c^2.

Lattice QCD



Non quark-antiquark J^{PC} , Exotic Quantum Numbers!

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EXOTIC HYBRID MESONS

Experimental evidence for a single state:

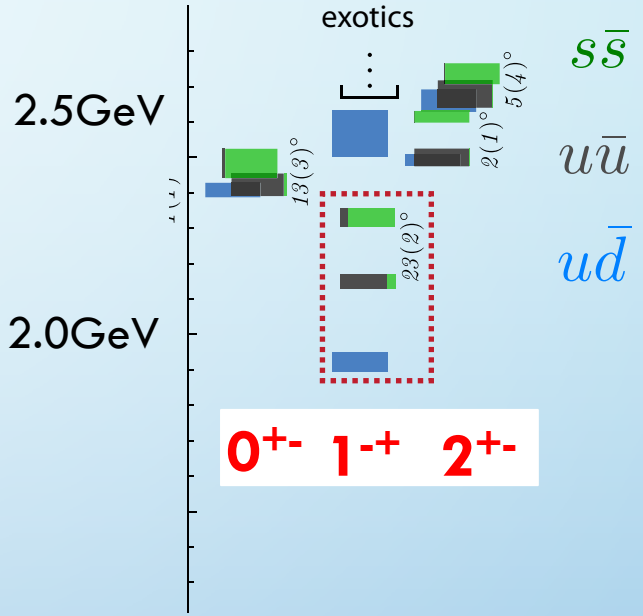
$\pi_1(1600)$

Reported in several experiments in several decay modes. Strongest observed signal is in

$\pi_1(1600) \rightarrow \eta'\pi$

Where are the other states?

Lattice QCD



$J^{PC}=0^{+-}$: b_0, h_2, h_0'

$J^{PC}=1^{-+}$: π_1, η_1, η_1'

$J^{PC}=2^{+-}$: b_2, h_2, h_2'

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Mode	Mass	Width	Experiment
3π	1598 ±8+29-47	168±20+150-12	E852
$\eta'\pi$	1597±10+45-10	340±40±50	E852,VES,COMPASS
$b_1\pi$	1664±8±10	185±25±38	E852,VES,CBAR
$f_1\pi$	1709±24±41	403±80±115	E852,VES
3π	1660 ±10+64-0	269±21+42-64	COMPASS

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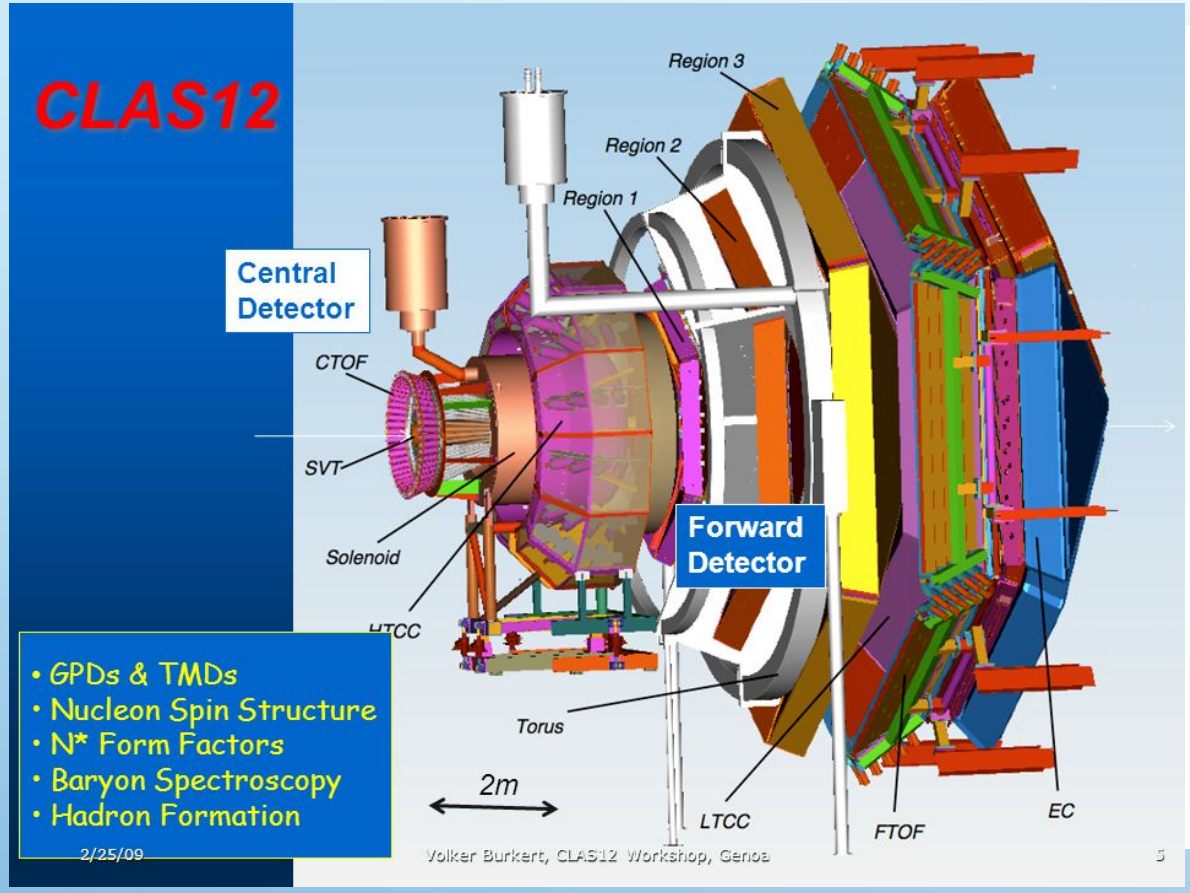
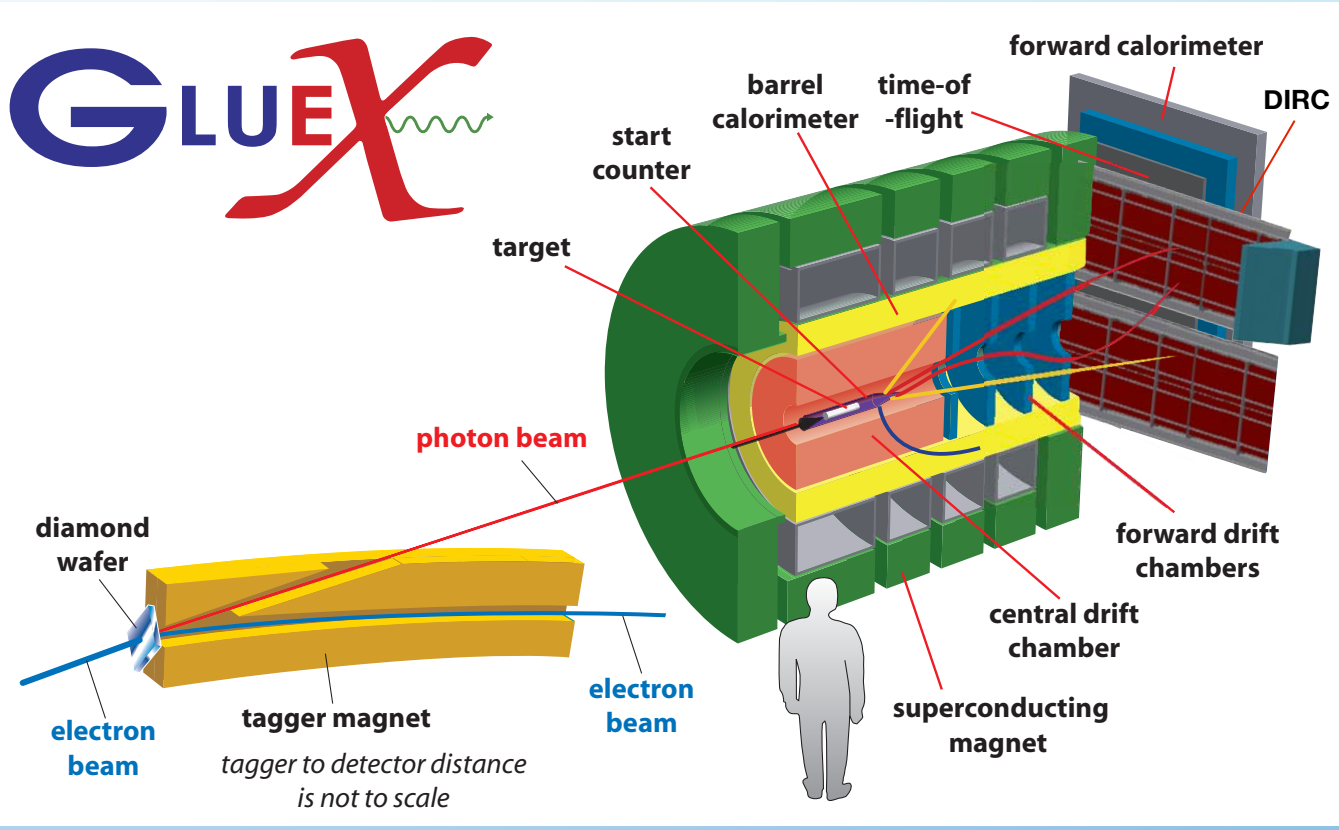
$f_1\pi$	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	E852,VES
3π	$1660 \pm 10^{+64}_{-0}$	$269 \pm 21^{+42}_{-64}$	COMPASS
$\eta'\pi$	**$1564 \pm 24 \pm 86$**	**$492 \pm 54 \pm 102$**	**JPAC**

Does glue manifest itself as an underlying degree of freedom in the hadronic spectrum?

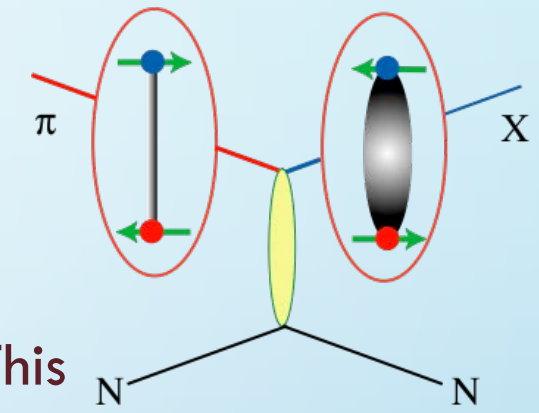
Spectroscopy Experiments for 12 GeV



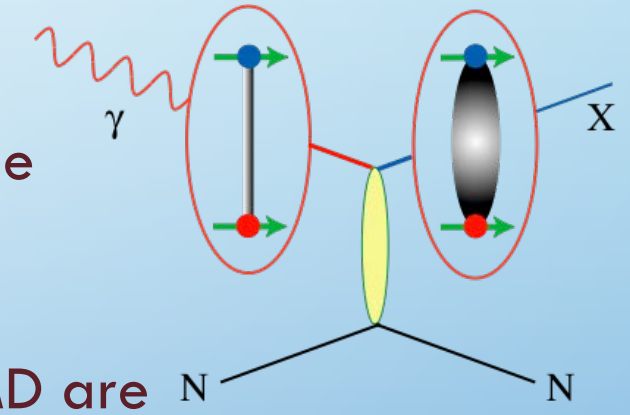


PHOTOPRODUCTION

- Over the last 15 years, low-energy ($E_\gamma < 4$ GeV) photoproduction experiments have helped to rewrite our understanding of baryon resonances.

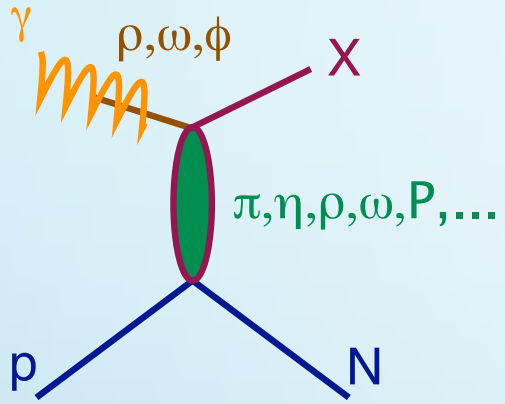


- Almost **no high-energy ($E_\gamma > 7.5$GeV)** photoproduction data exist. This is the regime where where t-channel processes dominate the production mechanisms.



- **Linearly-polarized photons** act as a filter on the naturality of the exchange mechanism.
- Photon beams are unique in that they have J=1, and through VMD are effectively beams of ρ, ω and ϕ mesons.
- Photon beams may be a good way to produce strangeonium states.

EXOTIC HYBRID PHOTOPRODUCTION MECHANISMS



Simple quantum number counting for production:
$(I^G)J^{PC}$ up to L=2

P = Pomeron exchange

$\rho\pi,\rho\omega \rightarrow \pi_1$
$\omega\omega,\rho\rho \rightarrow \eta_1$
$\omega\omega,\rho\rho,\phi\omega \rightarrow \eta'_1$
$\rho P \rightarrow b_0$
$\omega P \rightarrow h_0$
$\omega P, \phi P \rightarrow h'_0$
$\omega\pi,\rho\eta,\rho P \rightarrow b_2$
$\rho\pi,\omega\eta,\omega P \rightarrow h_2$
$\rho\pi,\omega\eta,\phi P \rightarrow h'_2$

$\rho\pi$ is charge-exchange only

Can couple to all the lightest exotic hybrid nonets through photo-production and VMD.

Linear polarization is a filter on the naturality of the exchanged particle.

Decay Modes of Exotic Hybrids

$\pi_1 \rightarrow \pi\rho,\ \pi b_1,\ \pi f_1,\ \pi\eta',\ \eta a_1$
$\eta_1 \rightarrow \eta f_2,\ a_2\pi,\ \eta f_1,\ \eta\eta',\ \pi(1300)\pi,\ a_1\pi,$
$\eta_1' \rightarrow K^*K,\ K_1(1270)K,\ K_1(1410)K,\ \eta\eta'$

$b_2 \rightarrow \omega\pi,\ a_2\pi,\ \rho\eta,\ f_1\rho,\ a_1\pi,\ h_1\pi,\ b_1\eta$
$h_2 \rightarrow \rho\pi,\ b_1\pi,\ \omega\eta,\ f_1\omega$
$h'_2 \rightarrow K_1(1270)K,\ K_1(1410)K,\ K_2^*K,\ \phi\eta,\ f_1\phi$

$b_0 \rightarrow \pi(1300)\pi,\ h_1\pi,\ f_1\rho,\ b_1\eta$
$h_0 \rightarrow b_1\pi,\ h_1\eta$
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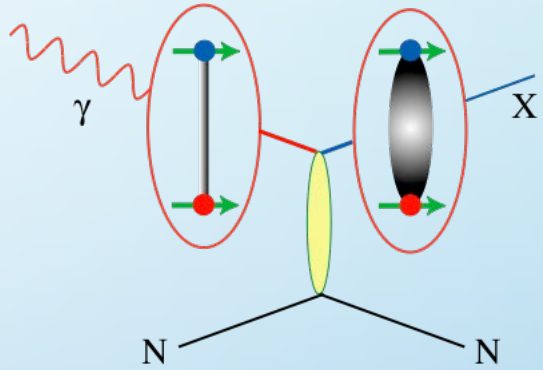

Early Reach **With Statistics** **Hard**

Hybrid kaons do not have exotic QN's

Models suggest narrower states are in the spin-1 and spin-2 nonets, while the spin-0 nonets are broad.

Decay Modes of Exotic Hybrids

$\pi_1 \rightarrow \pi\rho, \pi b_1, \pi f_1, \pi\eta', \eta a_1$
$\eta_1 \rightarrow \eta f_2, a_2\pi, \eta f_1, \eta\eta', \pi(1300)\pi, a_1\pi,$
$\eta_1' \rightarrow K^*K, K_1(1270)K, K_1(1410)K, \eta\eta'$

$b_2 \rightarrow \omega\pi, a_2\pi, \rho\eta, f_1\rho, a_1\pi, h_1\pi, b_1\eta$
$h_2 \rightarrow \rho\pi, b_1\pi, \omega\eta, f_1\omega$
$h'_2 \rightarrow K_1(1270)K, K_1(1410)K, K_2^*K, \phi\eta, f_1\phi$

$b_0 \rightarrow \pi(1300)\pi, h_1\pi, f_1\rho, b_1\eta$
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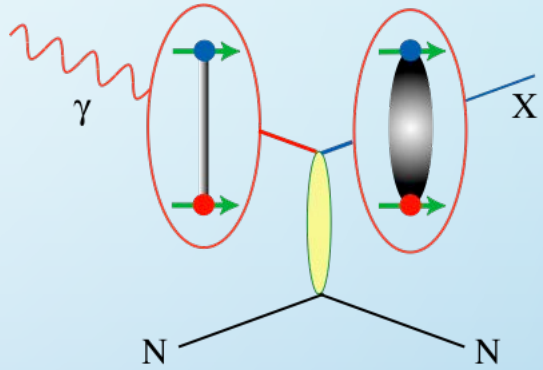

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$\eta_1' \rightarrow K^*K,\ K_1(1270)K,\ K_1(1410)K,\ \eta\eta'$

For a mass ~1600, too heavy

$b_2 \rightarrow \omega\pi,\ a_2\pi,\ \rho\eta,\ f_1\rho,\ a_1\pi,\ h_1\pi,\ b_1\eta$

$h_2 \rightarrow \rho\pi,\ b_1\pi,\ \omega\eta,\ f_1\omega$

$h'_2 \rightarrow K_1(1270)K,\ K_1(1410)K,\ K_2^*K,\ \phi\eta,\ f_1\phi$

$b_0 \rightarrow \pi(1300)\pi,\ h_1\pi,\ f_1\rho,\ b_1\eta$

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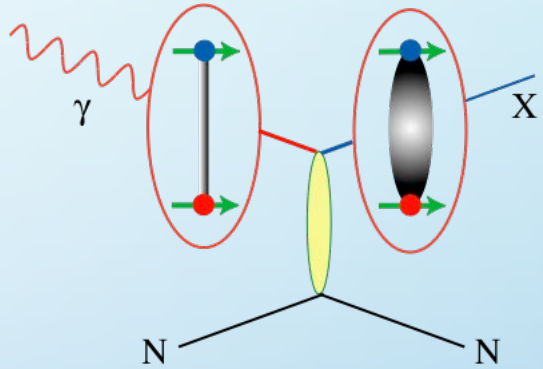

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THE SEARCH FOR HYBRIDS

GlueX is a discovery experiment utilizing a unique beam, hermetic detector, very sophisticated analyses.

GlueX will produce very large statistics in unexplored reactions.

CLAS12 will explore nearly-real photoproduction, covering many of the same final states as GlueX

Most exotic hybrid mesons could be photoproduced. We need to exclusively reconstruct many relevant final states.

Initial Searches:

$\pi_1(1600) \rightarrow \eta'\pi$ (known state)
$\pi_1(1600) \rightarrow \rho\pi$
$\eta_1 \rightarrow \eta\pi\pi$ (isospin partner)
$\eta'_1 \rightarrow K^*K$ (isospin partner)

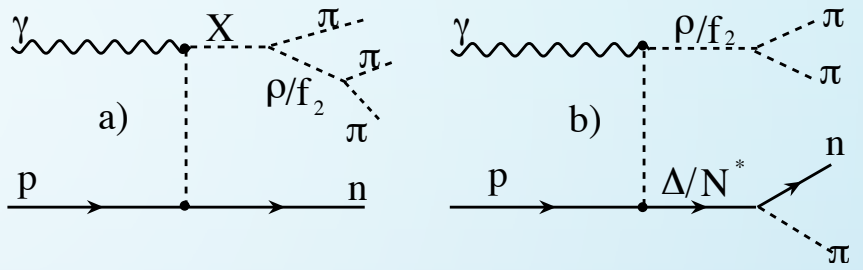
$b_2 \rightarrow \eta\pi\pi$ (other nonet)
$b_2 \rightarrow \omega\pi$ (other nonet)
$b_2 \rightarrow \rho\pi$ (other nonet)

Preliminary studies of these channels indicate interesting signals are present.

CLAS Results

$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

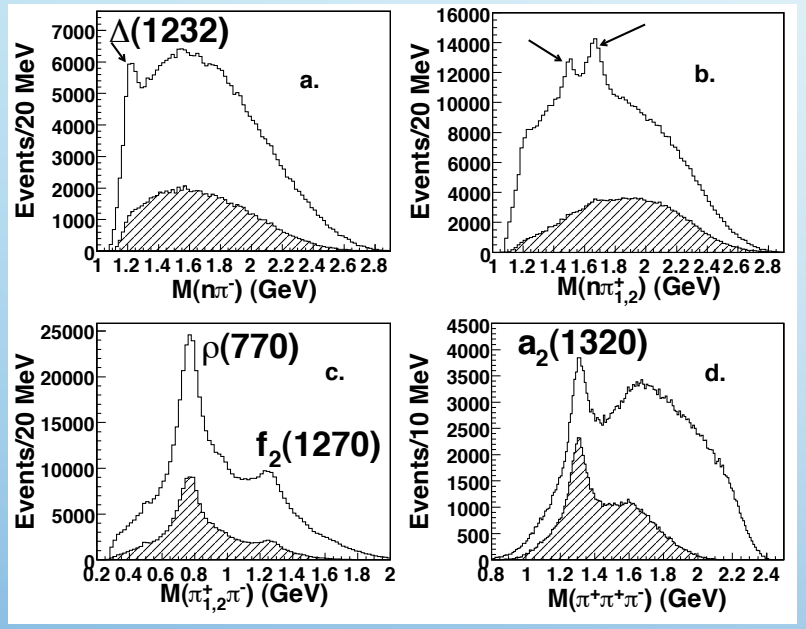
$E_\gamma = 4.8 - 5.4$ GeV



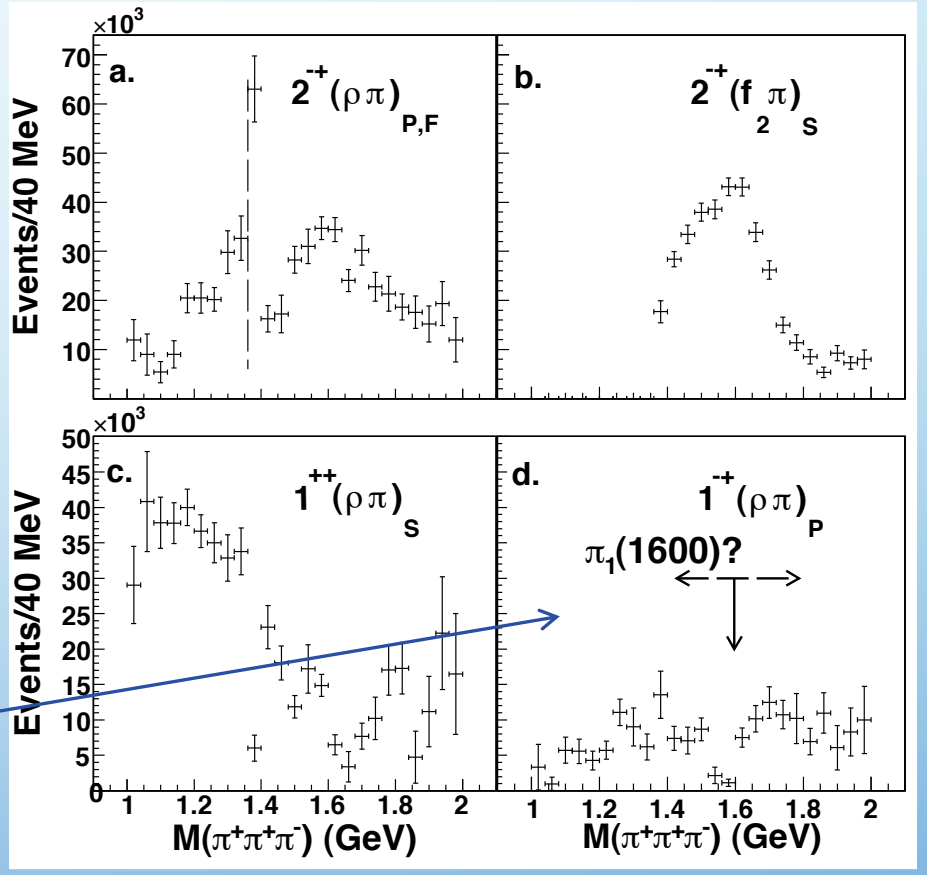
83000 Events after all cuts

Overall Acceptance < 5%

Baryons "removed" by kinematic cuts.



PWA



No evidence of $\pi_1(1600) \rightarrow \rho\pi$, (13.5 nb upper limit).

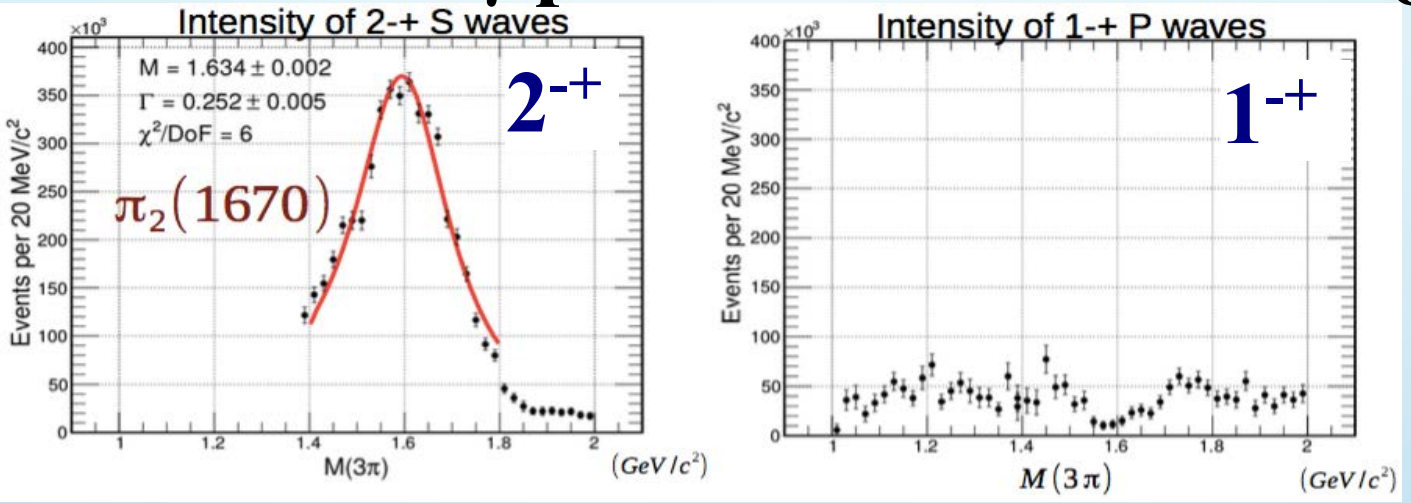
PRL 102, 102002 (2009)

Non-resonant 1^{-+} exotic wave

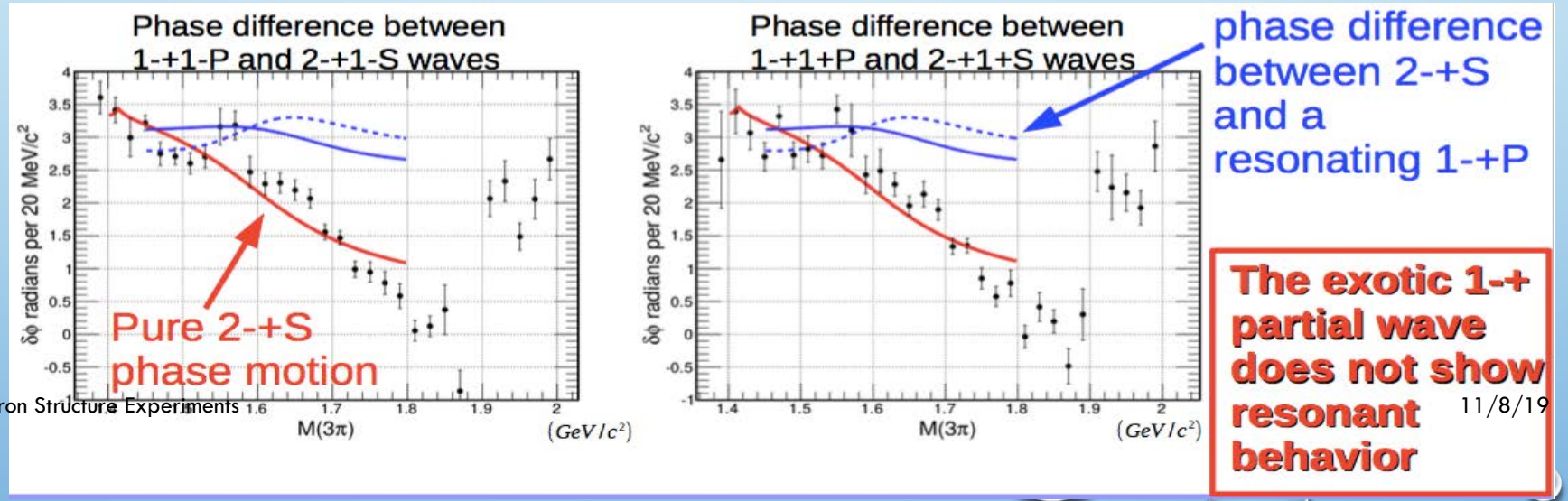
$$\gamma\, p \rightarrow n\ \pi^+\pi^+\pi^-$$

CLAS g12 ($E_\gamma < 5.5$ GeV)

preliminary



Much larger statistics, no signal for the $\pi_1(1600)$

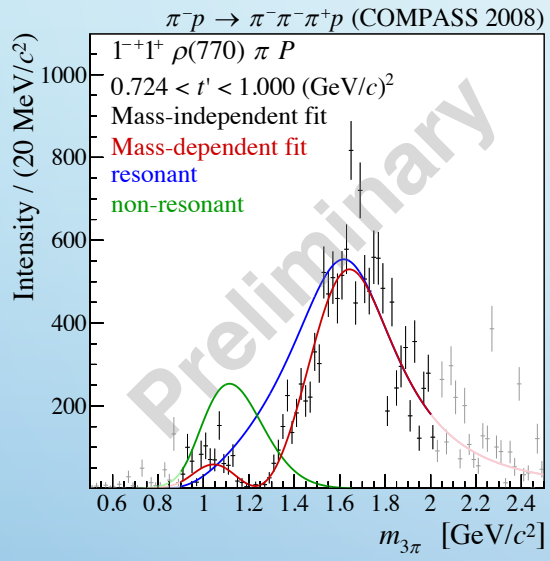


A. Tsaris (2016 FSU Dissertation) Slide from Paul Eugenio)

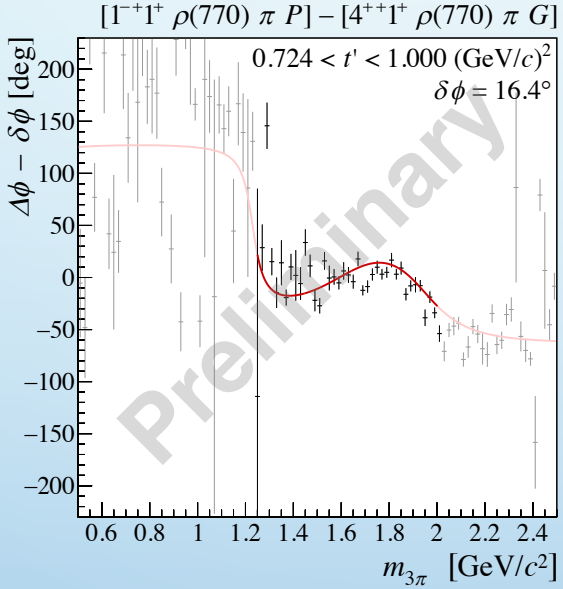
Compass Results on $\pi_1(1600)$ $\pi^- p \rightarrow p\pi^-\pi^+\pi^-$

In the $\rho\pi$ system at larger momentum transfer, $|t|$, they observe a signal with phase motion in the 1^{-+} exotic wave, the $\pi_1(1600)$.

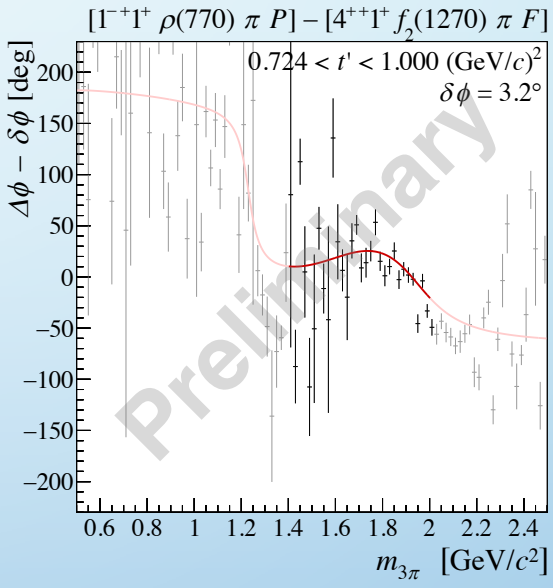
Intensity of 1^{-+}



Phase Difference to 4^{++}



Phase Difference to 4^{++}



Other reports in various decay modes from E852, VES and others.

Phys. Rev. D98, 092003 (2018)

THE SEARCH FOR HYBRIDS

GlueX is a discovery experiment utilizing a unique beam, hermetic detector, very sophisticated analyses.

GlueX will produce very large statistics in unexplored reactions.

CLAS12 will explore nearly-real photoproduction, covering many of the same final states as GlueX

Most exotic hybrid mesons could be photoproduced. We need to exclusively reconstruct many relevant final states.

Initial Searches:

$\pi_1(1600) \rightarrow \eta'\pi$ (known state)

$\pi_1(1600) \rightarrow \rho\pi$

$\eta_1 \rightarrow \eta\pi\pi$ (isospin partner)

$\eta'_1 \rightarrow K^*K$ (isospin partner)

$b_2 \rightarrow \eta\pi\pi$ (other nonet)

$b_2 \rightarrow \omega\pi$ (other nonet)

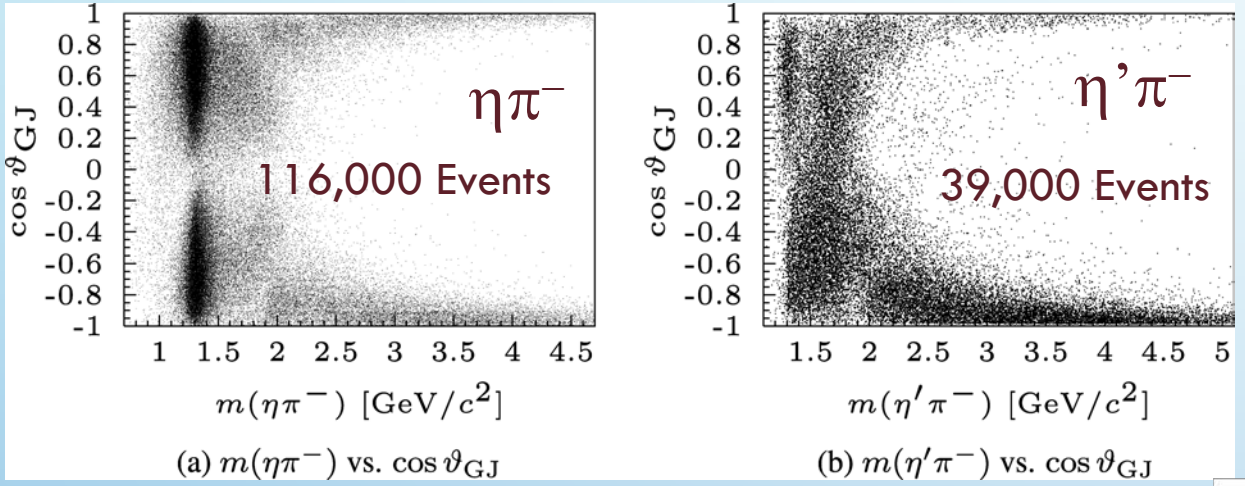
$b_2 \rightarrow \rho\pi$ (other nonet)

Preliminary studies of these channels indicate interesting signals are present.

INTERESTING HYBRID CHANNELS

Highest statistics on $\pi_1(1600) \rightarrow \eta'\pi$ from COMPASS

$\pi^- p \rightarrow p\ \eta\pi^-$ $\pi^- p \rightarrow p\ \eta'\pi^-$

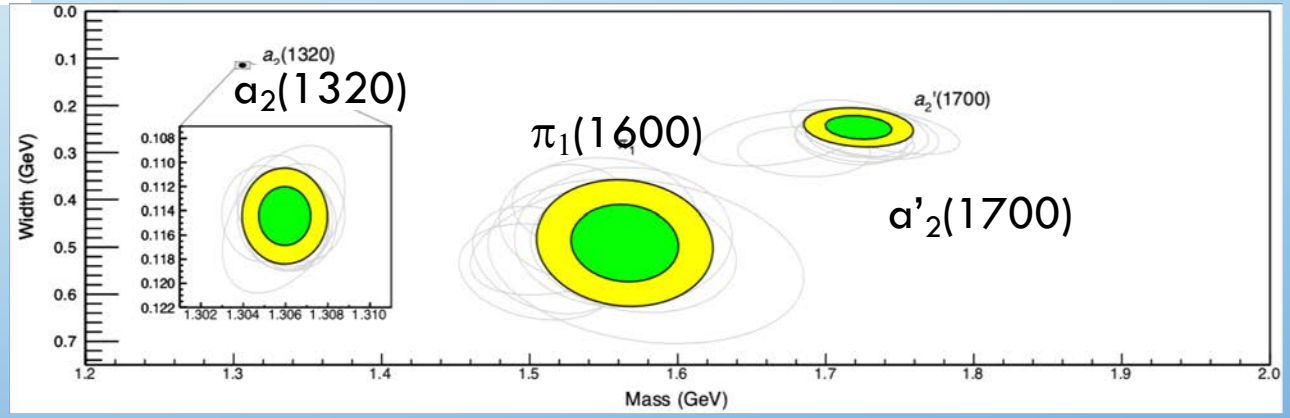


JPAC: Extracted the pole position of the $\pi_1(1600)$ from the COMPASS amplitudes.

Mass: 1564 +/- 24 +/- 86 MeV

Width: 492 +/- 54 +/- 102 MeV

COMPASS: strong exotic wave in the $\eta'\pi^-$, but not in the $\eta\pi^-$ data.

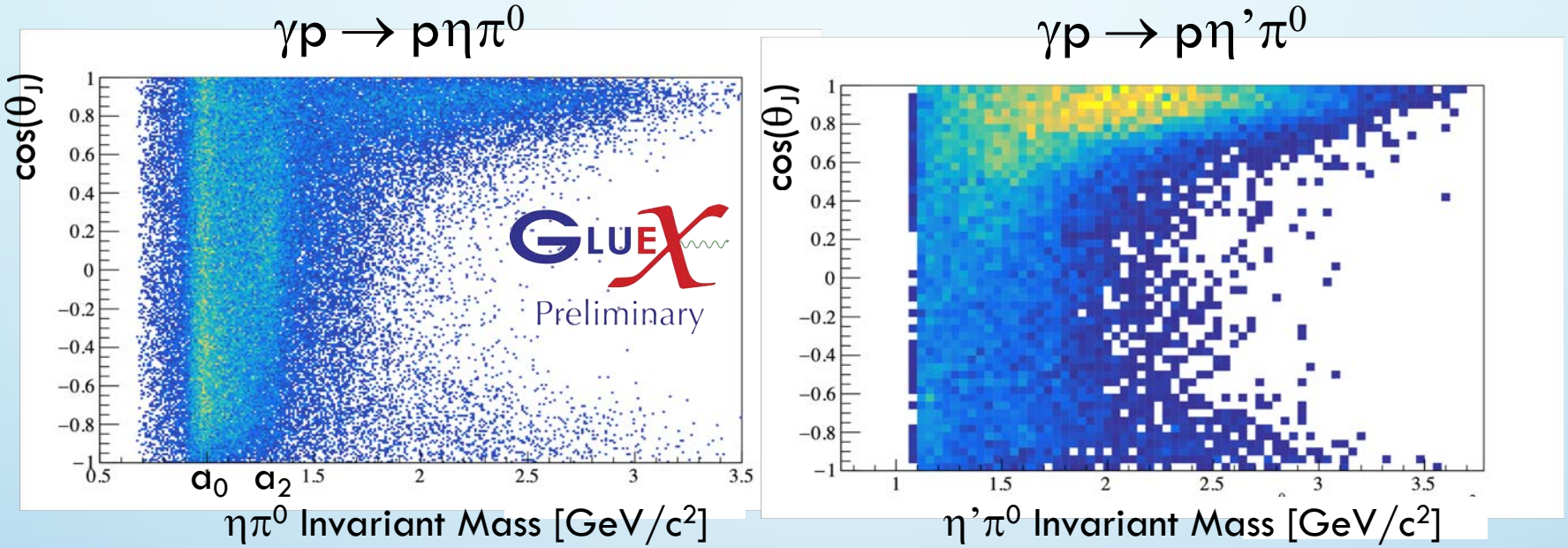


COMPASS: Phys. Lett. B 740, 303 (2015).

JPAC: Phys. Rev. Lett. 122, 042002 (2019)

INTERESTING HYBRID CHANNELS

First GlueX Hybrid Search



In same decay modes as COMPASS, GlueX will have 280,000 $\eta\pi^0$ and 52,000 $\eta'\pi^0$ events in the full data set (versus COMPASS with 116,000 & 39,000).

Charge exchange reaction is also being studied.

$\gamma p \rightarrow \Delta^{++}\eta\pi^-$

$\gamma p \rightarrow \Delta^{++}\eta'\pi^-$

These analyses are underway, using the full phase I data set.

INTERESTING HYBRID CHANNELS $\gamma p \to p\eta\pi^+\pi^-$

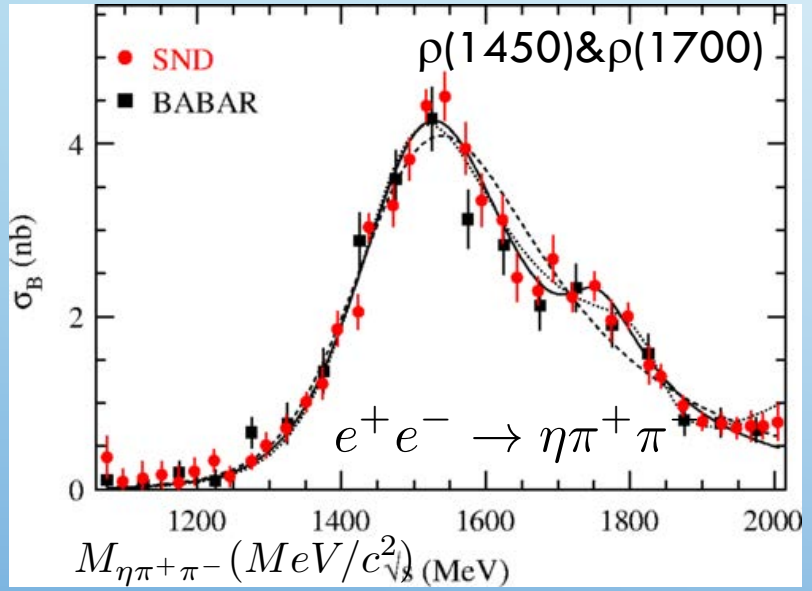
SND/BaBar: e^+e^- to $\eta\pi^+\pi^-$
C=– states: $\rho(1450)$, $\rho(1700)$

What can we learn from other experiments?

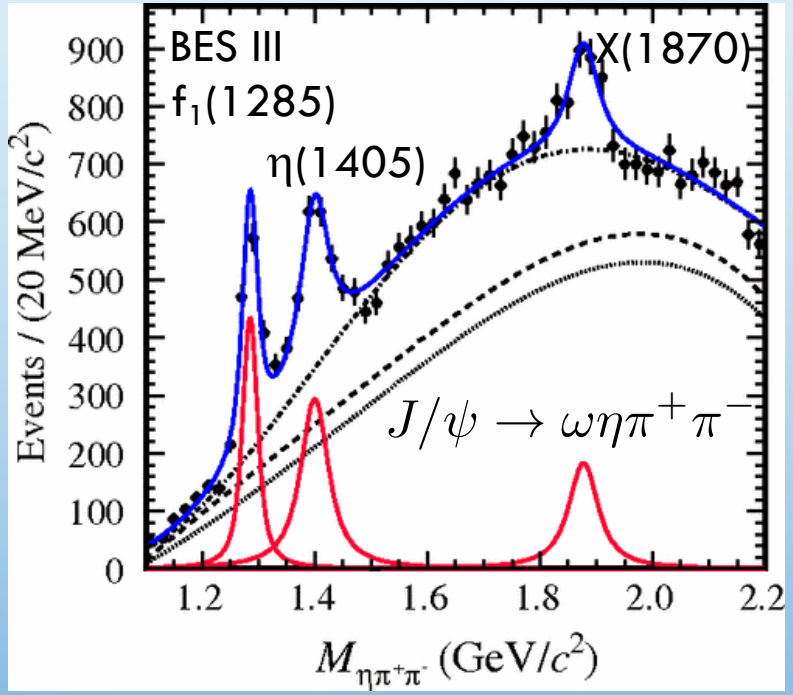
BES III: J/ψ decays to $\eta\pi^+\pi^-$ recoiling against ω
C=+ states: $\eta'(958)$, $f_1(1285)$, $\eta(1405)$ and X(1870)

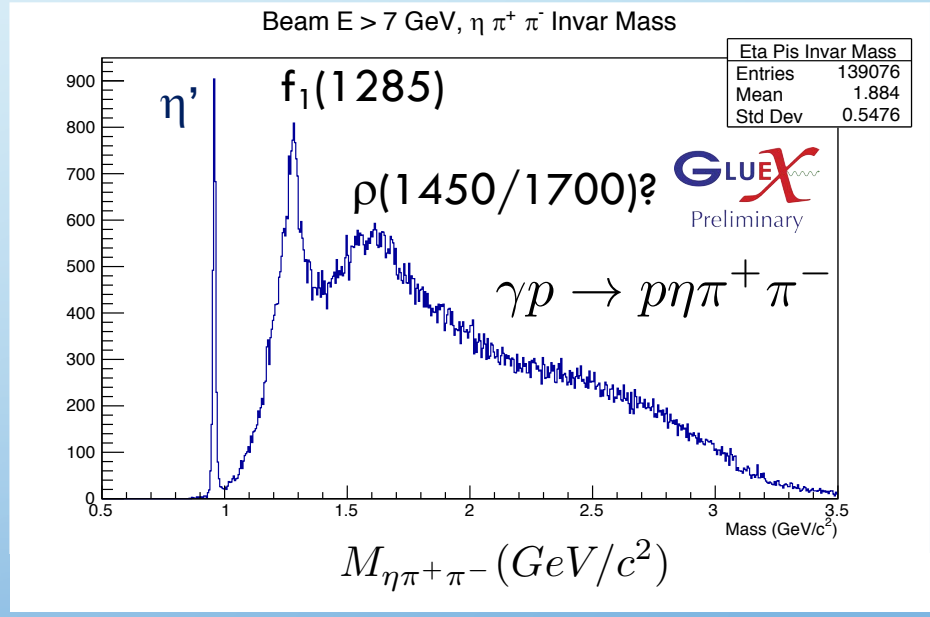
GlueX: Photoproduction
$\eta'(958)$, $f_1(1285)$
C+ and C– states

Phys. Rev. D 97, 012008



Phys. Rev. Lett. 107, 182001





INTERESTING HYBRID CHANNELS $\gamma p \rightarrow p\eta\pi^+\pi^-$

$\gamma p \rightarrow p\eta_1$ $\qquad$ $\gamma p \rightarrow p b_2$

$\eta_1 \rightarrow \eta f_2, a_2^{+-}\pi^{-+}$ $\qquad$ $b_2 \rightarrow \eta\rho, a_2\pi$

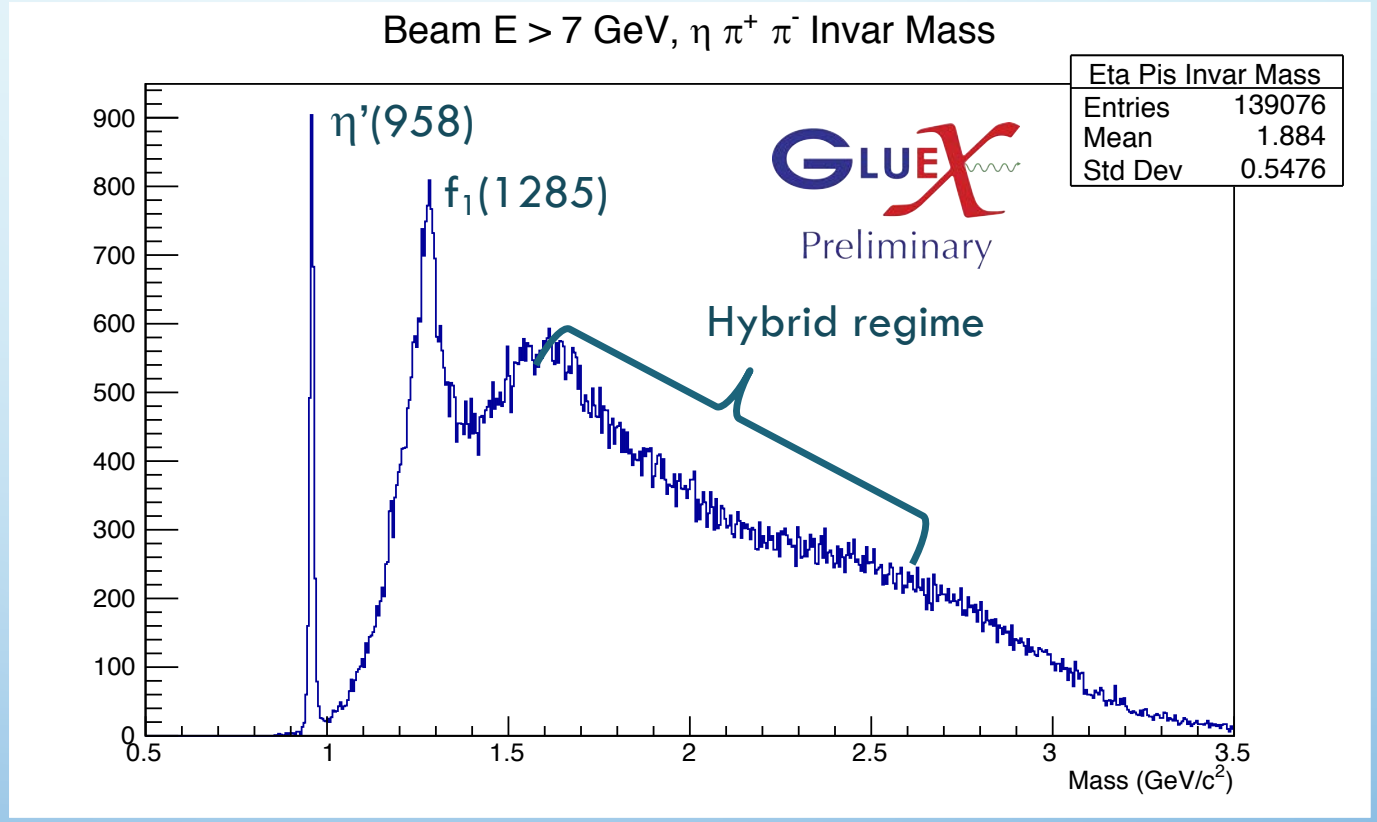
$\rho \rightarrow \pi\pi$
$f_2 \rightarrow \pi\pi$
$a_2 \rightarrow \eta\pi$

Look for these

$\gamma p \rightarrow p a_2^{+-}\pi^{-+}$

$\gamma p \rightarrow p f_2 \eta$

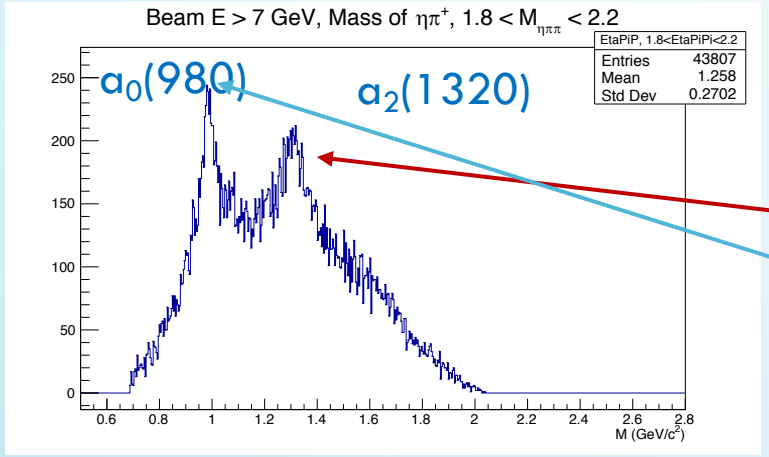
$\gamma p \rightarrow p\rho\eta$



$m(\eta\pi\pi)$

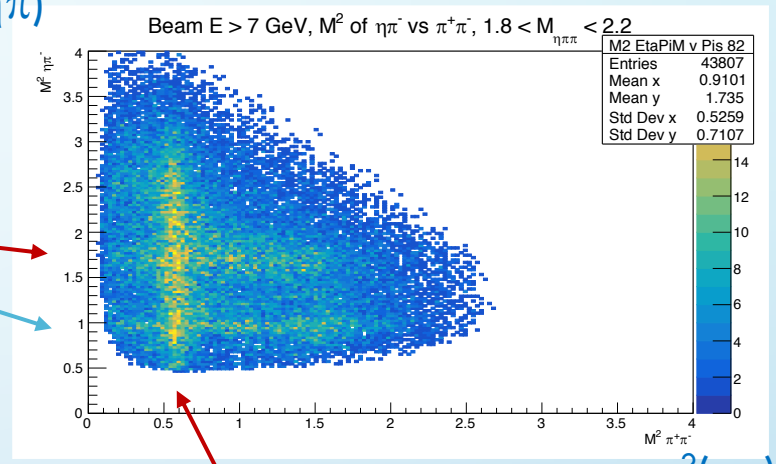
2016 Engineering Run $\qquad$ 80 hours of beam

INTERESTING HYBRID CHANNELS $\gamma p \rightarrow p\eta\pi^+\pi^-$

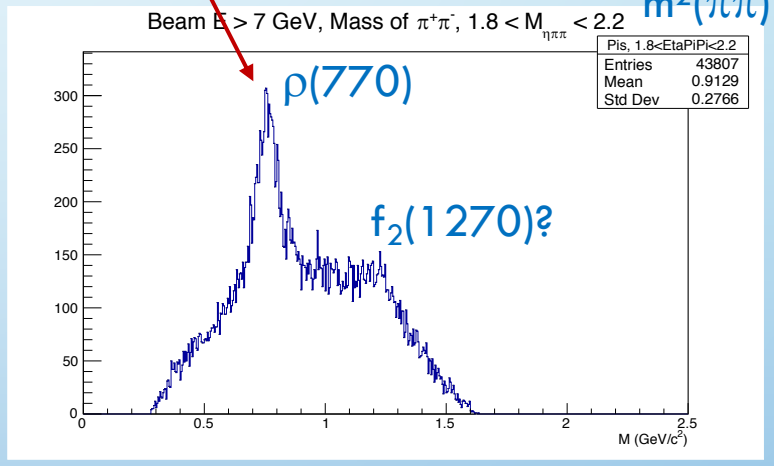


$m(\eta\pi)$

$m^2(\eta\pi)$



$m^2(\pi\pi)$



$m(\pi\pi)$

Clear signals for

$\gamma p \rightarrow p a_2^{+-}\pi^{-+}$

$\gamma p \rightarrow p f_2 \eta$

Weak signal for

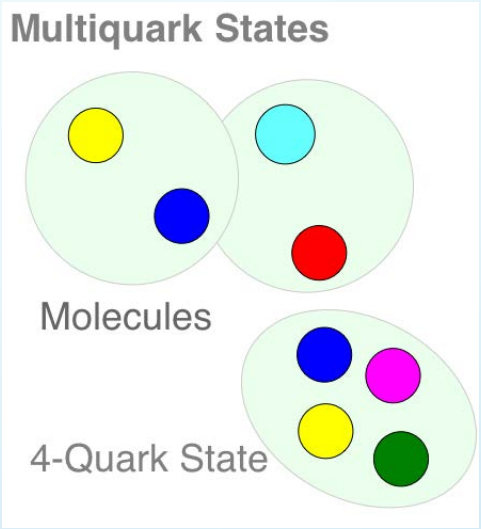
$\gamma p \rightarrow p \rho \eta$

GlueX Preliminary

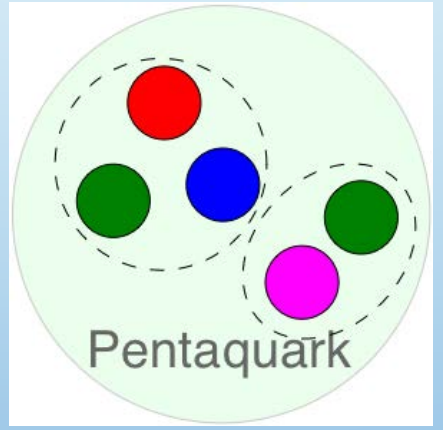
Important hybrid decay channels are present in photoproduction.
Enough data have been collected to start these searches.

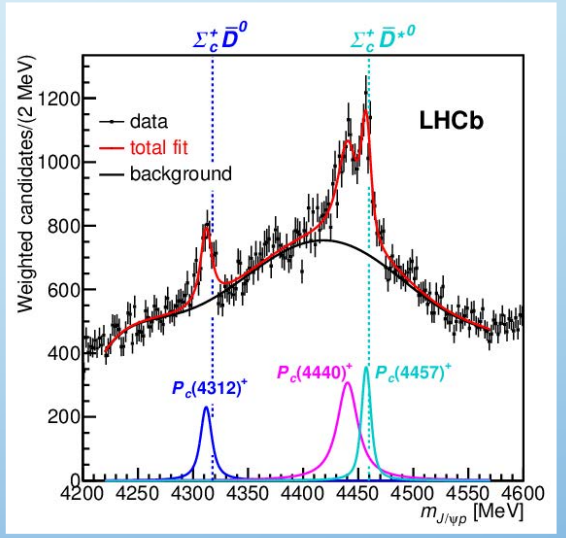
$m(\pi\pi)$

ANOTHER TYPE OF EXOTIC



The LHCb experiment has recently reported on pentaquark candidates involving charm quarks.



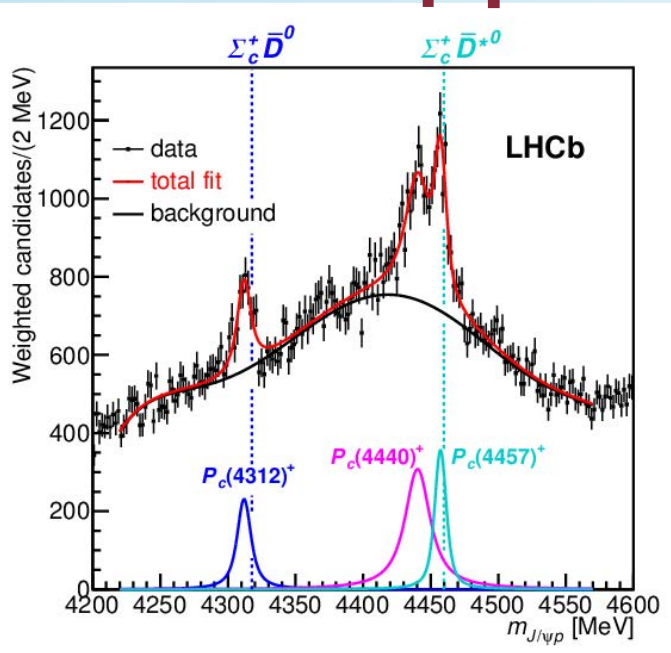


J/Ψ PHOTOPRODUCTION NEAR THRESHOLD

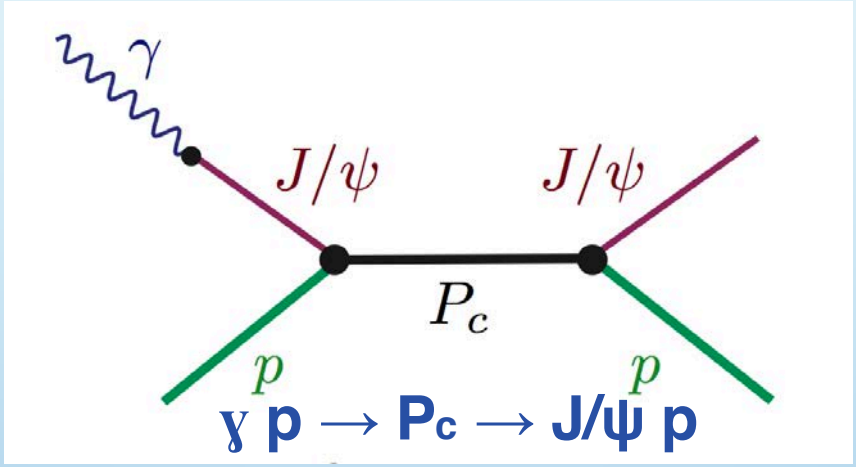
Threshold production is experimentally clean, ideal for studying J/ψ+N interaction.

Study coupling of resonant J/ψ+p states to photon.

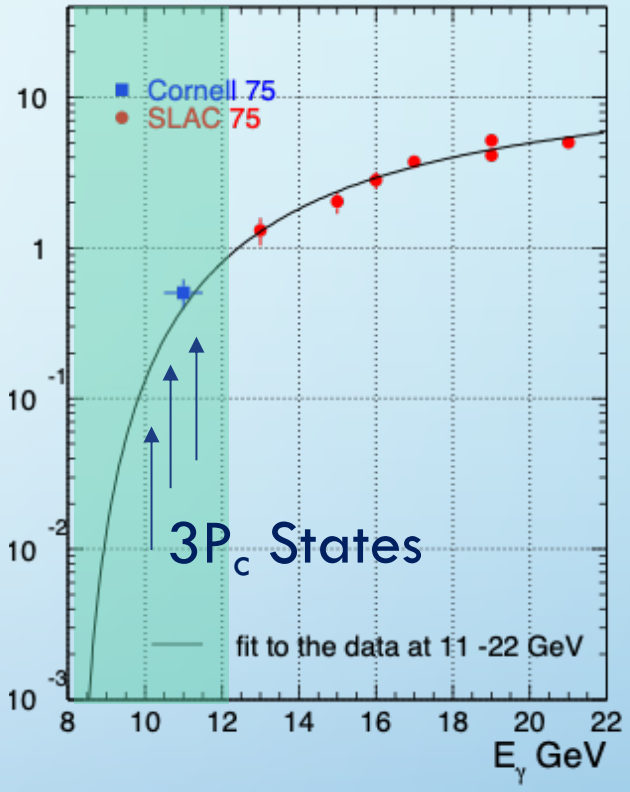
$\Lambda_b \rightarrow J/\psi\ p\ K^-$



Phys. Rev. Lett. 122, 222001 (2019)

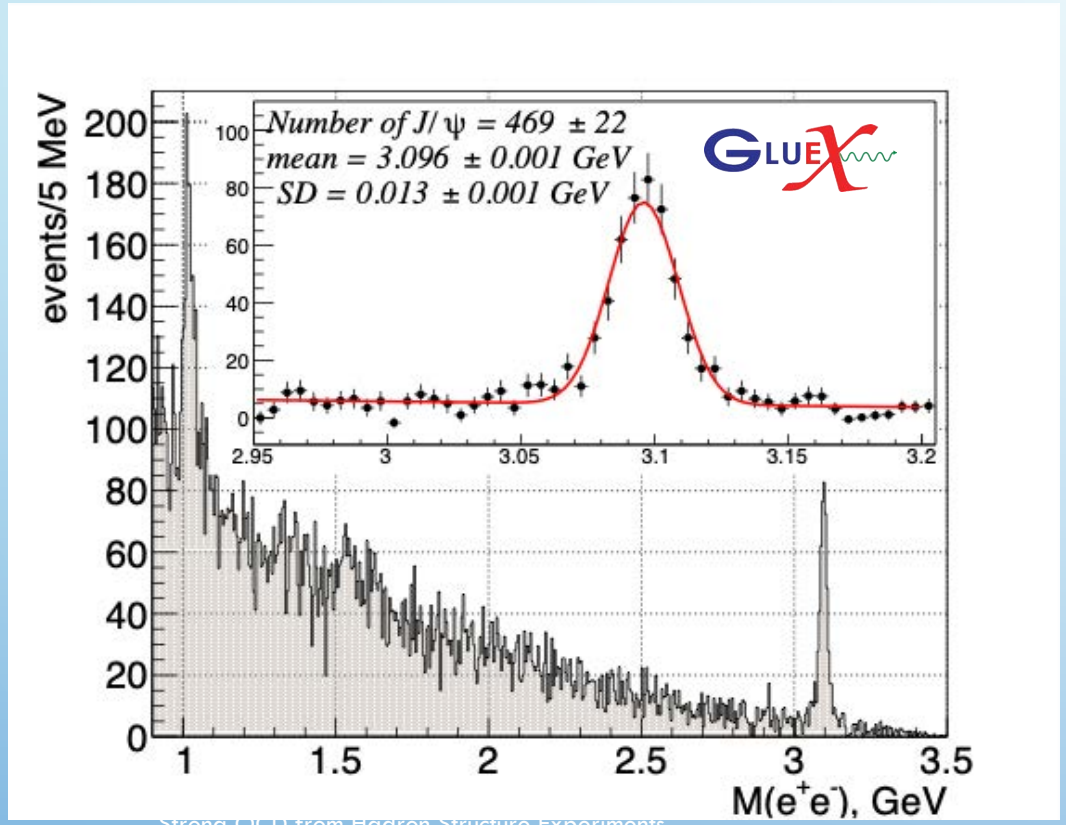


s-channel photoproduction probes nature of 5-quark interaction!

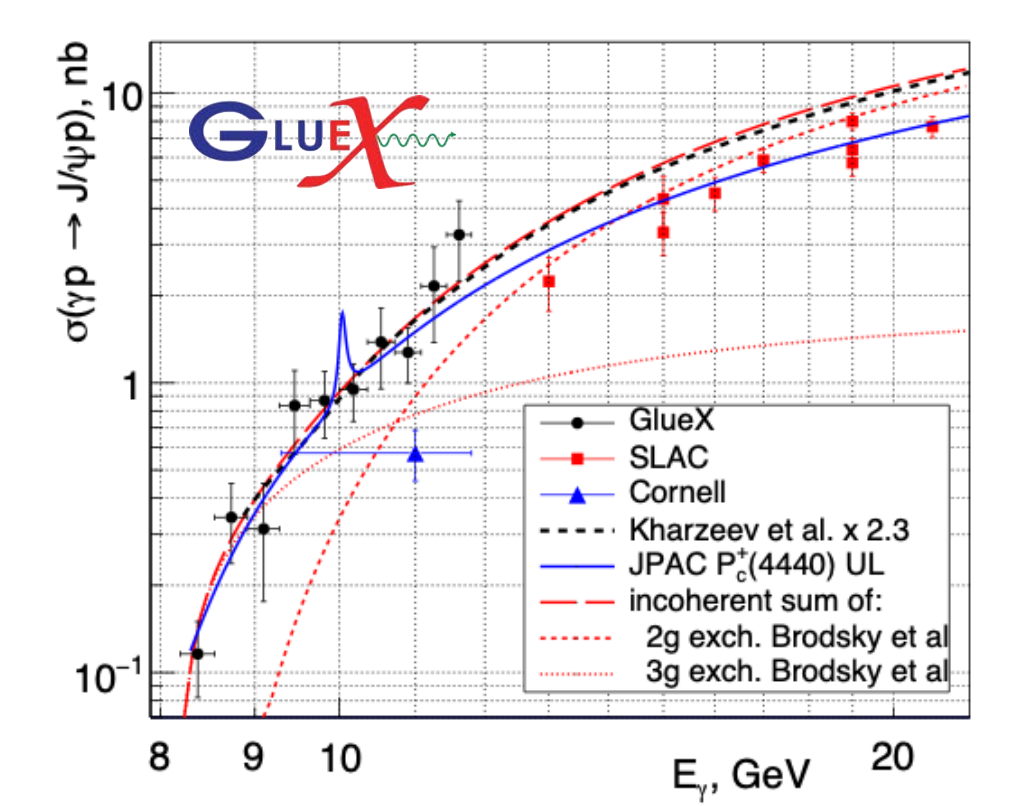


J/Ψ PHOTOPRODUCTION

First J/ψ cross section measurement at threshold, 27% normalization uncertainty, 3x as much data collected.



Phys. Rev. Lett. **123,** 072001 (2019)



JPAC A.N. Hiller Blin, et al., PRD 94, 034002 (2016).

Model-dependent upper limits at 90% CL:

Br(**Pc(4312)** → J/ψ p) **< 4.6%**

Br(**Pc(4440)** → J/ψ p) **< 2.3%**

Br(**Pc(4457)** → J/ψ p) **< 3.8%**

SUMMARY AND OUTLOOK

- The ERA of 12-GeV exotic searches has begun.
- GlueX and CLAS12 are both running.
- GlueX has collected a large initial data set that is currently in active physics analysis.
- I expect that we will start to see results of some analyses within a year.